ARMY RESEARCH LABORATORY

Staged Ram Accelerator Experiments With Unique Projectile Geometries

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ARL-TR-1219 October 1996

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1996	Final, Mar 95 - Feb 96

4. TITLE AND SUBTITLE

Staged Ram Accelerator Experiments With Unique Projectile Geometries

5. FUNDING NUMBERS

PR: 1L162618AH80

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-1219

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

First experiments using multiple propellant stages and unique projectile geometries in the U.S. Army Research Laboratory (ARL) ram accelerator are reported. New criteria for comparative analysis of experiments based on both total heat release and heat release rate are introduced and evaluated relative to these experiments. Finally, experimental data indicating that projectile material can influence the desired experiments through burning and heat release are presented.

14. SUBJECT TERMS

ram accelerator, multistage, hypervelocity gun, subsonic combustion, supersonic combustion

15. NUMBER OF PAGES

17

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

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ACKNOWLEDGMENTS

The authors wish to thank Mr. Michael Nusca for critical insights provided by his companion CFD research; Mr. Robert Hall for continued experimental support; and Mr. Albert Horst and Dr. Thomas Minor for continued technical and programmatic support.

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1. INTRODUCTION

Ram acceleration is initiated by injection of a projectile, similar in shape to the center body of a ramjet engine, into a tube filled with a combustible gaseous fuel/oxidizer/diluent, or simply propellant. As the subcaliber projectile and obturator enter the propellant at supersonic speeds, shock and viscous heating occurs. This heating ignites and sustains combustion on the aft section and behind the projectile. This energy release occurs continuously as the projectile accelerates. It is often useful to adjust the propellant composition down the length of the accelerator tube to ensure high efficiency of combustion in accelerating the projectile. In practice, this is accomplished by segmenting the accelerator tube with thin plastic diaphragms to separate the propellants. The fuel's components may be changed such that its properties (i.e. sound speed and chemical energy) are adjusted to maximize projectile acceleration (Knowlen, Bruckner, and Hertzberg 1992). The use of multiple fuels by segmenting the accelerator is often referred to as "staging" the accelerator.

The U.S. Army Research Laboratory (ARL) has been exploring in-bore ram acceleration as a technique to obtain hypervelocities with useful (5-10 kg) projectile masses. The research has consisted of an integrated program of experiment and computational modeling. Past research has investigated scaling and pressure effects and flow visualization (Kruczynski 1992; Kruczynski 1993a; Kruczynski 1993b). Current research is ongoing in the areas of projectile geometry and staging effects.

2. FACILITY

2.1 Accelerator and Injection Gun. The ARL facility was created by removing the breeches of 120-mm M256 tank guns and mating the tubes. Each accelerator section (tube) is 4.7 m long. Currently, three accelerator tubes are available for a total combined accelerator length of 14.1 m. The accelerator tubes may be segmented with PVC diaphragms and filled with different propellant gases or used without diaphragms for longer runs with single propellant mixtures. The projectile is brought up to injection speed (typically 1,200 m/s) using a conventional 120-mm tank gun and a solid propellant. Projectile transition to the first accelerator tube is made through a vented tube section. This section serves to both decouple the conventional gun recoil (through a sliding interface) and vent solid propellant gases to minimize interference with the ram acceleration process. Figure 1 shows the layout of the facility.

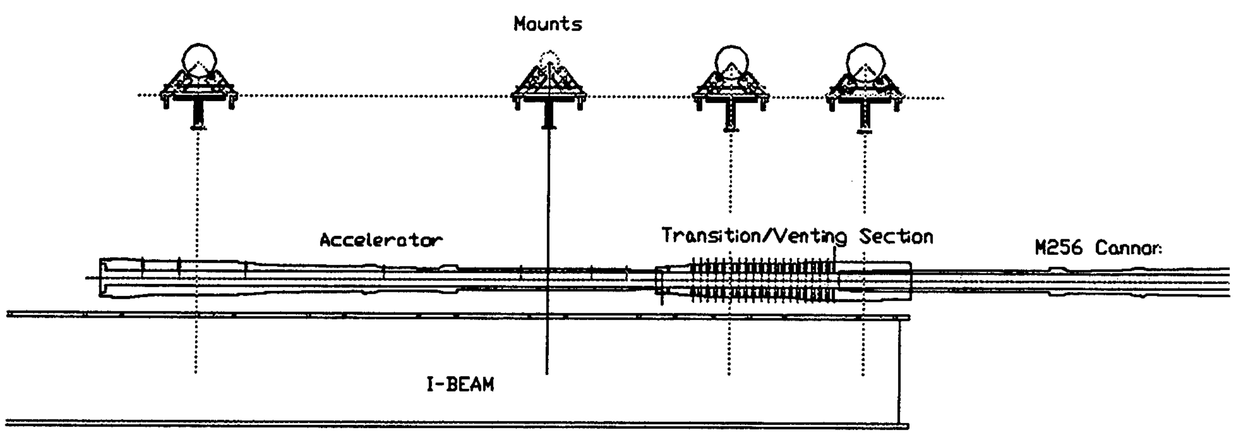

Figure 1. ARL ram accelerator with one accelerator tube.

2.2 Gas Handling and Mixing. A bank of gas storage bottles supplies the required gases. It should be noted that ram acceleration propellant components are readily available at bottled gas dealers in standard highway transportable storage bottles. The ARL facility also includes a compressor capable of charging the accelerator to 340 atm. Recent additions to the facility include a premix station and online gas chromatography for analyzing the propellant mixtures used. The premix station was installed to avoid any ambiguity about the content and homogeneity of the propellant and is particularly useful for multistage firings since the gas mixtures may be mixed, tested, and adjusted in advance.

Prior to installation of the premix station, the accelerator tubes in the ARL facility were directly filled with the desired propellant by partial pressure methods. Samples taken from the accelerator before firing (but analyzed days later) indicated that, in general, the actual propellant mixtures were in reasonable agreement with intended mixtures. However, it was suspected that the propellant mixture was not homogeneously mixed prior to firing (it was thought that mixing was being completed in the small sample bottles). When the portable gas chromatography (GC) system was installed, these suspicions were confirmed. Table 1 shows data from a two-accelerator tube shot in which the same mixture was simultaneously pumped into both tubes. Samples from both accelerator tubes were then taken and analyzed immediately after filling (about 10 min apart).

Table 1. Analysis of Propellant Mixtures Taken at Different Locations in the Accelerator Tubes

Shot/Stage and Fill Pressure	Mixture Component and Order of Fill	Desired Volume % (both stages)	GC* Analysis of Stage 1	GC Analysis of Stage 2
26/1 & 2 at 57 atm	CH_4	20	15	22
	O_2	13	15	14
	N_2	67	70	64

* GC is gas chromatography.

Table 1 shows a considerable discrepancy between the two samples.

The premix station consists of a bank of standard 44-liter gas bottles (initially mounted vertically), which are remotely filled from the individual source gases many hours (or days) before firing. Using the on-line GC, the banks of bottles may be sampled at any time and their contents adjusted if necessary. Analysis of the premixed gases over extended periods of time revealed that, in general, 48 hr or longer is required to ensure the gases have "completely" mixed by diffusion and residual turbulence from the filling process. This can be seen in the samples taken from the first stage mixture of shots 34 and 35 shown in Table 2. In the future, experiments with horizontally mounted bottles will be undertaken to reduce mixing times further.

When the propellant mixture appears to be within reasonable agreement with the desired mixture, it is ready to be pumped to the accelerator tube for firing. In addition, if desired, multiple shots may be made from the same premixed batch of propellant, ensuring repeatability. To date, no safety problems have been encountered handling these premixed, typically fuel rich, propellants.

Table 2. Measurement of Propellant Mixtures Over Time

Shot/Stage Number and Mixture Pressure	Mixture Component*	Desired Volume Percent in Mixture	**GC Result After 20 hr	GC Result After 48 hr	GC Result After 68 hr	GC Result After 140 hr	GC Result After 204 hr
34/1 at 81 atm	CH_4	20	45	--	17	17	--
	O_2	13	9	--	14	14	--
	N_2	67	46	--	69	69	--
35/1 at 81 atm	CH_4	20	--	17	--	--	17
	O_2	13	--	14	--	--	14
	N_2	67	--	69	--	--	69

* Mixtures were filled in nine steps using one-third of each gas in each step.
**GC is gas chromatography.

3. STAGING EXPERIMENTS - RATIONALE, RANKING CRITERIA, AND TEST MATRIX

It has been well documented (Knowlen, Bruckner, Hertzberg 1992) that peak performance for a ram accelerator, operating below the Chapman-Jouget detonation speed, is obtained when the total heat release of the propellant (typically defined as $\frac{\Delta q}{C_p T}$) is kept as high as possible and the projectile's relative Mach number as low as possible. However care must be exercised so that the flow neither gas-dynamically chokes (becomes sonic) at the projectile's throat (area of minimum clearance between projectile body and the tube wall) nor disgorges a normal shock through the throat from behind, during excessive heat addition (an unstart). Finding the optimum conditions may be dependent on the scale and design of the projectile. In addition, the conditions during initial projectile injection into the accelerator from the injector gun (obturator discard, etc.) may require that the initial propellant be characterized by lower heat release than propellant for "steady" operation (Kruczynski, Liberatore, Kiwan 1993).

ARL has only recently expanded its facility to the point where the "optimum" conditions for efficient operation (after the initial startup) are being explored. Due to the relatively high cost of experimental operation at 120-mm bore size, great care is taken in designing new experimental firing sequences in order to maximize the insights gained from each firing. In the case of the firings reported in this report, a qualitative ranking system was used to screen experiments. The ranking system is based on three simple comparative factors for analyzing the experimental potential of a shot. The first two factors, available heat release $\frac{\Delta q}{C_p T}$ and projectile Mach number (relative to the propellant), were briefly discussed previously and are further detailed in Knowlen, Bruckner, and Hertzberg (1992).

The third factor is the rate at which heat is released, as calculated using a methane/air combustion mechanism developed by the Gas Research Institute consisting of 32 species and 176 reactions. This mechanism is used in conjunction with the SENKIN kinetics code run at constant pressure with an initial temperature derived from previous computational fluid dynamics (CFD) runs. Further details on the use of this method are available in Nusca (1995). Using large kinetics mechanisms in CFD calculations results in prohibitively long computer run times. Therefore, kinetics codes such as SENKIN should provide information for screening new fuel mixtures and making comparative analyses, reducing the need for additional CFD calculations.

The first shot in the staging experiments (shot 34) was designed to evaluate the potential for operating the 120-mm ram accelerator at elevated (relative to the starting stage) heat release values. The second and third accelerator tubes were filled with the more energetic mixture. No attempt was made in this experiment to adjust sound speed of the mixture. Since this shot was successful, it became the baseline for comparison with subsequent shots. Note that in all the shots in this series, the initial stage of the ram accelerator contained nominally the same propellant which has shown excellent repeatability in previous ARL experiments (Kruczynski 1992; Kruczynski 1993a; Kruczynski 1993b). The second and third firings of the series were designed to maximize acceleration by raising the heat release and sound speed of the propellant. This would allow both "high" $\frac{\Delta q}{C_p T}$ and low Mach number operation. The final shot of the series was made with the same propellant as in shot 34; however, both the projectile design and materials were different. This projectile contained a short constant diameter section (92 mm long) between the nose and aft sections. This "isolator" design was evaluated for its potential in preventing unstarts and is fully reported in Kruczynski and Liberatore (1995). A drawing of the "standard" projectile is seen in Figure 2. Table 3 summarizes properties for these experiments. Note that the total heat release values (Q/CpT) were equal to or less than that of shot 34, in subsequent shots, while the release times for the shots after shot 34 were approximately equal or longer than the baseline shot 34.

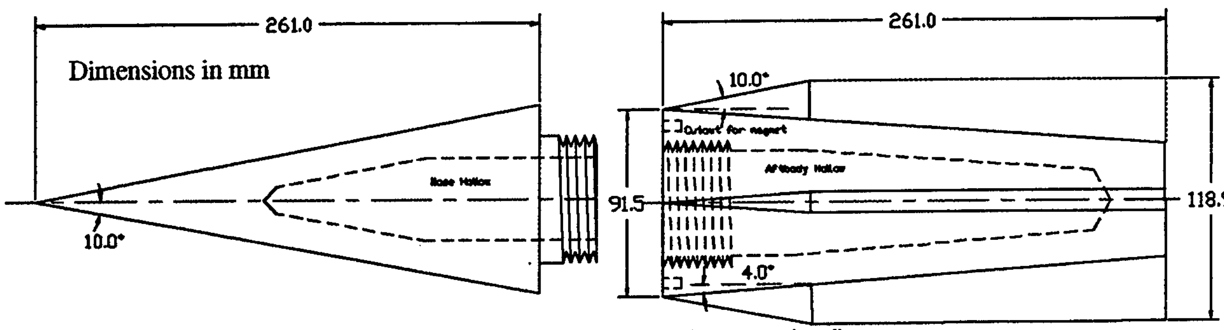

Figure 2. 120-mm standard ram projectile.

Table 3. Comparison of Propellant Properties

Shot No.	Stage 1 - Propellant Properties (1Tube)			Stage 2 - Propellant Properties (2 tubes)			Notes
	Q/c_pT	Release[2] Time (ms)	Entrance Mach No.	Q/c_pT	Release Time (ms)	Entrance Mach No.	
34	3.7	0.54	3.3	5.23	0.34	3.7	Standard Projectile
Moles[1]	2.5 CH_4 + 2.0 O_2 + 9.9N_2			2.4 CH_4 + 2.0 O_2 + 5.8 N_2			
35	3.7	0.54	3.3	3.95	0.41	3.1	Very Slight Mod[3]
Moles	2.5 CH_4 + 2.0 O_2 + 9.9 N_2			2.9 CH_4 + 2.0 O_2 + 3.5 N_2 + 4.1 He			
36	3.49	0.51	3.4	3.99	0.38	2.9	Standard Projectile
Moles	2.8 CH_4 + 2.0 O_2 + 9.6 N_2			5.0 CH_4 + 2.0 O_2 + 4.0 He			
37	3.71	0.50	3.4	4.33	0.36	3.93	Proj. With Isolator[4]
Moles	2.6 CH_4 + 2.0 O_2 + 9.0 N_2			2.7 CH_4 + 2.0 O_2 + 6.3 N_2			

[1] Molar content gas chromatography analysis
[2] Approximate time to maximum energy release at given temperature (1,350 K) and constant pressure (further details on the use of this method are available in Nusca)
[3] Small backward facing steps behind throat between fins (see Kruczynski and Liberatore)
[4] See projectile description above

4. EXPERIMENTAL RESULTS

The first shot of the series (34) exhibited successful ram acceleration in all three accelerator tubes. Photos of the projectile in flight after exit showed no damage. This shot then became the "standard" against which the succeeding tests were compared.

Shot 35 successfully accelerated through the first tube but unstarted (combustion moved forward and past the projectile midbody) 2.355 m into the stage two propellant mixture. The projectile's image was captured in-flight at exit from the last accelerator tube. The projectile appeared to be completely intact; this ruled out any question of projectile mechanical failure causing the unstart. The very slight modifications to the projectile noted in Table 3 above did not appear to be involved in the unstart based on its performance in the successful run of the first accelerator stage. Note that the unstart occurred even though the propellant mixtures in accelerator tubes two and three had equal or lower $\frac{\Delta q}{C_p T}$ values and longer release times than the previous shot.

Shot 36 successfully accelerated through the first stage mixture but again unstarted about halfway into the stage two propellant mixture. Again, an image of the projectile after exit from the accelerators revealed no structural damage. Note that this projectile design was identical to that of shot 34 and the fuels in accelerator tubes two and three again had lower $\frac{\Delta q}{C_p T}$ and longer release times.

Shot 37 used a significantly different projectile geometry and was fired primarily to evaluate the performance of projectiles with constant diameter sections (isolators) in ram accelerators. To make direct comparisons with previous "standard" projectiles, the mid and aft sections were made from a high-strength magnesium alloy (ZK-60) to reduce total projectile mass to that of the "standard" projectile design. The nose section was aluminum with a stainless steel tip like the other shots (see Figure 2). Again the projectile had successful ram acceleration in the first stage. Like the previous two shots, it unstarted (violently) in the middle of the second accelerator. This occurred even though the fuel mixture was the same as that of shot 34 which operated successfully throughout. There was very strong photographic and material evidence that the projectile was burning in the second stage of the accelerator. A photo of the projectile after exit was not obtained because extreme light emission overexposed the film. Residue from burning magnesium was scattered throughout the accelerator. The reason this test is included in this report, which is concerned primarily with kinetics and staging effects, is because projectile material burning obviously contributed to the heat addition of the ram cycle and sparked a separate study (Liberatore 1995) looking into the effects on propellant kinetics of the projectile's material. This is discussed further in the next section.

A plot of velocity vs. travel for the four cases previously mentioned may be seen in Figure 3.

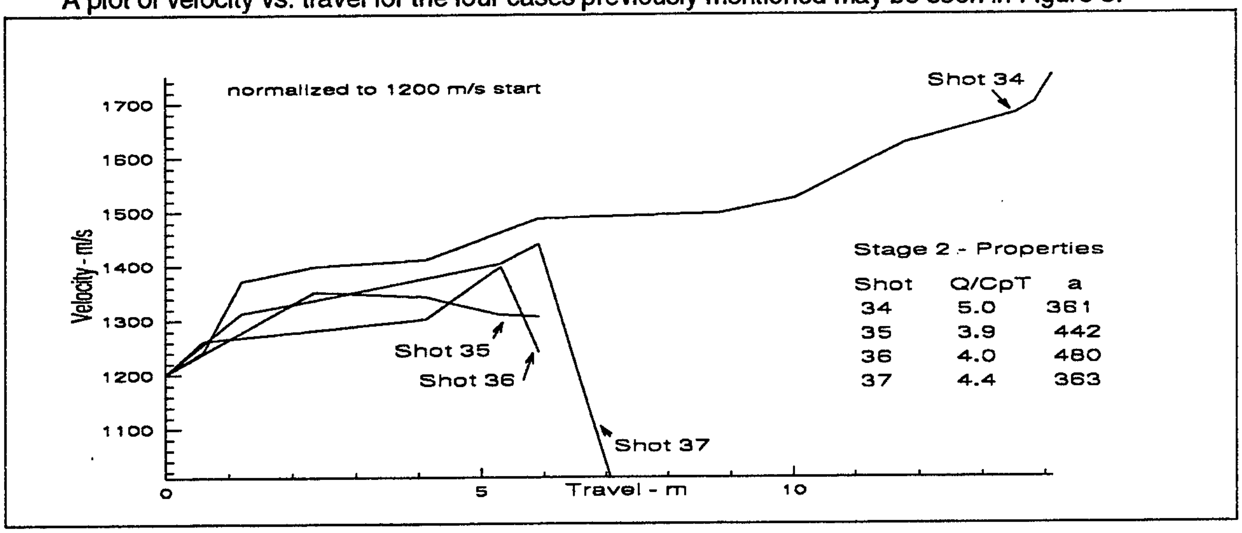

Figure 3. Velocity vs. travel.

5. ANALYSIS

Gas dynamic unstarts occurred in both attempts to raise the propellant's sound speed (by adding He), even though other calculated properties, such as total heat release and release times, were lower (or equal) and longer respectively for these experiments. Since the heat content value $\frac{\Delta q}{C_p T}$ has been used and validated extensively as an experimental parameter, it was decided to re-examine the assumption used in calculating the "heat release time." The first and perhaps most important consideration for these calculations is the temperature selected to begin the combustion calculation. For the cases reported to date, an "average" temperature in the boundary layer behind the initial bow and reflected shocks, over an average range of expected projectile Mach numbers, was used. The calculations used in setting these conditions were from previous shots in the ARL first stage "standard" fuel. The initial temperature was set at 1,350 K.

Following the unstarts of shots 35 and 36, it was decided to examine the CFD calculations of the flow of shot 36 to assess an "average temperature" using a similar method to that described previously. It was found that despite the projectile's lower Mach number in the helium mixtures, the average temperature in the flow was about 50 K higher. It is believed that the lower heat capacity of atomic species, in this case helium (with three energy degrees of freedom) as compared to that of diatomic nitrogen (five energy degrees of freedom) may account for this difference. When the "heat release rate" calculations were redone starting at 1,400 K, the release time was found to be shorter than that for the nitrogen diluted mixtures. The new release times for shots 35 and 36 were calculated to average 0.24 ms. When compared to the previously calculated average of 0.40 ms at 1,350 K it appears that relatively minor temperature changes can make a considerable difference in the kinetic calculations. Therefore, the initial conditions for such calculations must be considered carefully.

As noted earlier, the magnesium projectile (shot 37) did burn and may have contributed significantly to the projectile unstart through this unplanned and excessive heat release. Indeed there is some evidence from the photographs of the aluminum projectiles, which survived unstarts (shots 35 and 36), that there may also be some burning around the projectile's base, although this is not conclusive at this time. It is known that aluminum projectiles are failing and perhaps burning at higher Mach numbers (Patz et al. 1995). If the projectiles do burn, they will have a significant effect on the amount of energy being released around the projectile. This could be responsible for some unexplained unstarts. A study of this potential was done at ARL and is reported separately (Liberatore 1995).

6. CONCLUSIONS

A comparative method of screening new ram accelerator propellant mixtures, incorporating both total heat release and heat release times, has been suggested. Experiments and subsequent analysis revealed that care must be taken in determining the initial conditions for these calculations.

A projectile design, which incorporates a constant diameter mid-section, has been successfully fired through the rigorous starting phase of a ram accelerator.

Finally, experiments reveal that burning projectile material may produce unstarts through unplanned energy release.

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